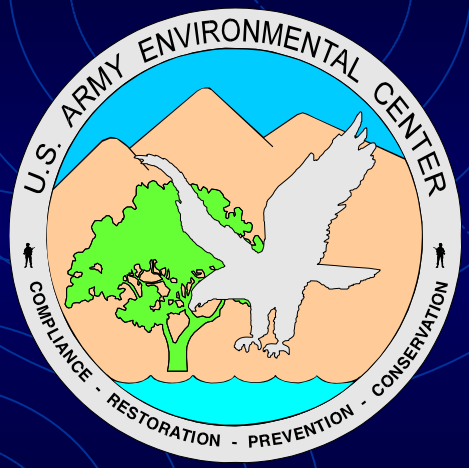
An Evaluation of Borehole Flowmeters Used to Measure Horizontal Ground-Water Flow in Limestones of Indiana-Kentucky-Tennessee, 1999

Martin R. Risch, presenter, DODEC 2000

U.S. Geological Survey in cooperation with the U.S. Army Environmental Center



John T. Wilson, Wayne A. Mandell, Frederick L. Paillet,

E. Randall Bayless, Randall T. Hanson, Peter M. Kearl,
William B. Kerfoot, Mark Newhouse, William H.

Overview of Presentation

- Use of Borehole Flowmeters
- Project Concept
- Description of Flowmeters Evaluated
- Evaluation of Flowmeters
- Interim Observations

Use of Borehole Flowmeters

- Conventional geophysical techniques identify bedrock features of potential flow.
- Conventional vertical flowmeters identify bedrock features that actually flow.
- Horizontal flowmeters measure direction and velocity of horizontal flow.
- Flowmeter data can be used for site assessment, flow models, and remediation planning.

Project Concept

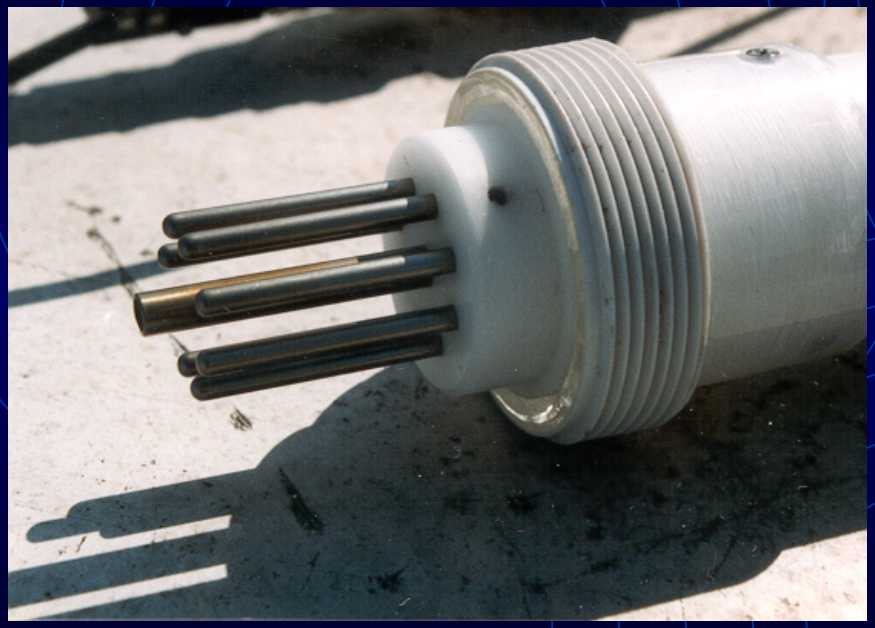
- Army Environmental Center has technical oversight of environmental restoration.
- Army bases are underlain by limestone bedrock modified by fracturing and dissolution.
- Trials with vertical and horizontal heat-pulse flowmeters were favorable.
- Evaluation of available horizontal flowmeter techniques was needed.

Description of Directional Borehole Flowmeters Evaluated

(Principles, Tools, Methods)

- Heat-pulse dissipation (KVA flowmeter)
- Video particle tracking (colloidal borescope)
- Acoustic attenuation (acoustic doppler velocimeter)
- Borehole dilution (hydrophysical logging)

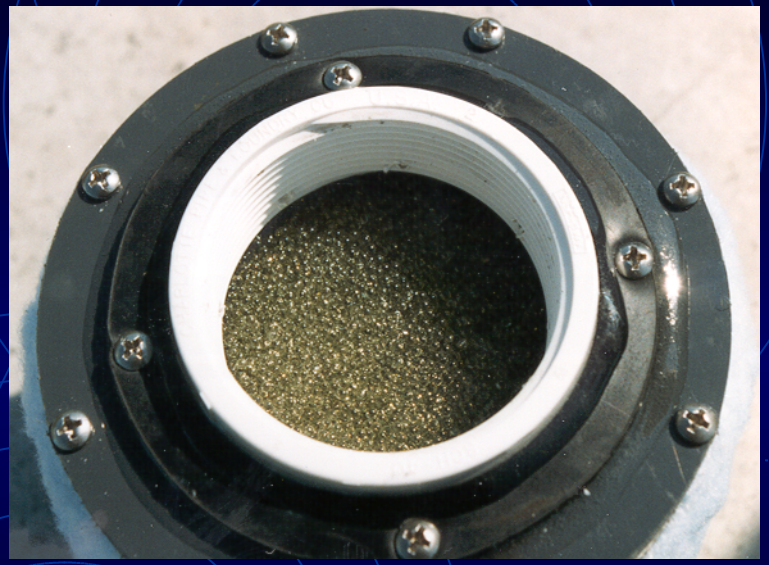
KVA Heat-Pulse Flowmeter



Probe tip with heat-pulse generator and thermistor temperature sensors

Control box with readout (in thermistor machine-units)

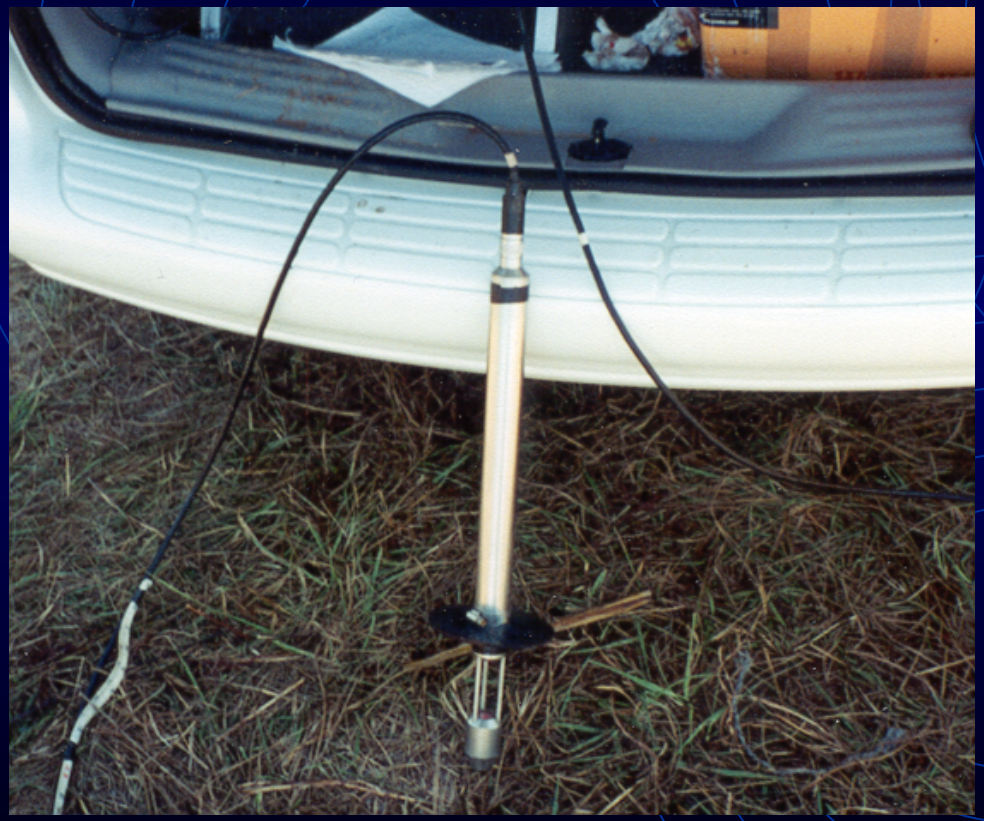
KVA Heat-Pulse Flowmeter



Glass beads inside packer

Probe with “fuzzy packer”

Colloidal Borescope



Probe with cable

Probe tip: lens, camera, light

Acoustic Doppler Velocimeter

Doppler probe with acoustic emitter and three receivers

Deployment into well

Hydrophysical Logging

ogging tool with 3 fluid conductivity
nd temperature sensors

alibration of fluid conductivity probes

Hydrophysical Logging

Making Deionized Water

Fluid management system

Evaluation of Flowmeters

- Study areas: Jefferson Proving Ground, IN and Fort Campbell, KY-TN
- Selection of test wells and background geophysical logging
- Arrangements for flowmeters & hydrophysics

Study Areas

Jefferson Proving Ground

- (2) 200-ft, 5-in. wells tested
- Limestone layer with vuggy porosity & other layers of limestone & shaley limestone
- Flat [illegible] rift

Fort Campbell

- (3) 161-ft, 6.25 in. wells tested
- Massive limestone with one to three dissolution-enhanced cavities along bedding planes
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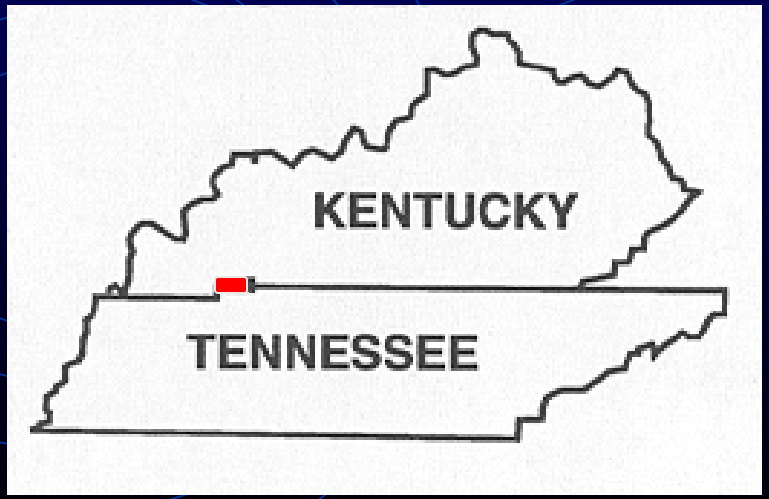
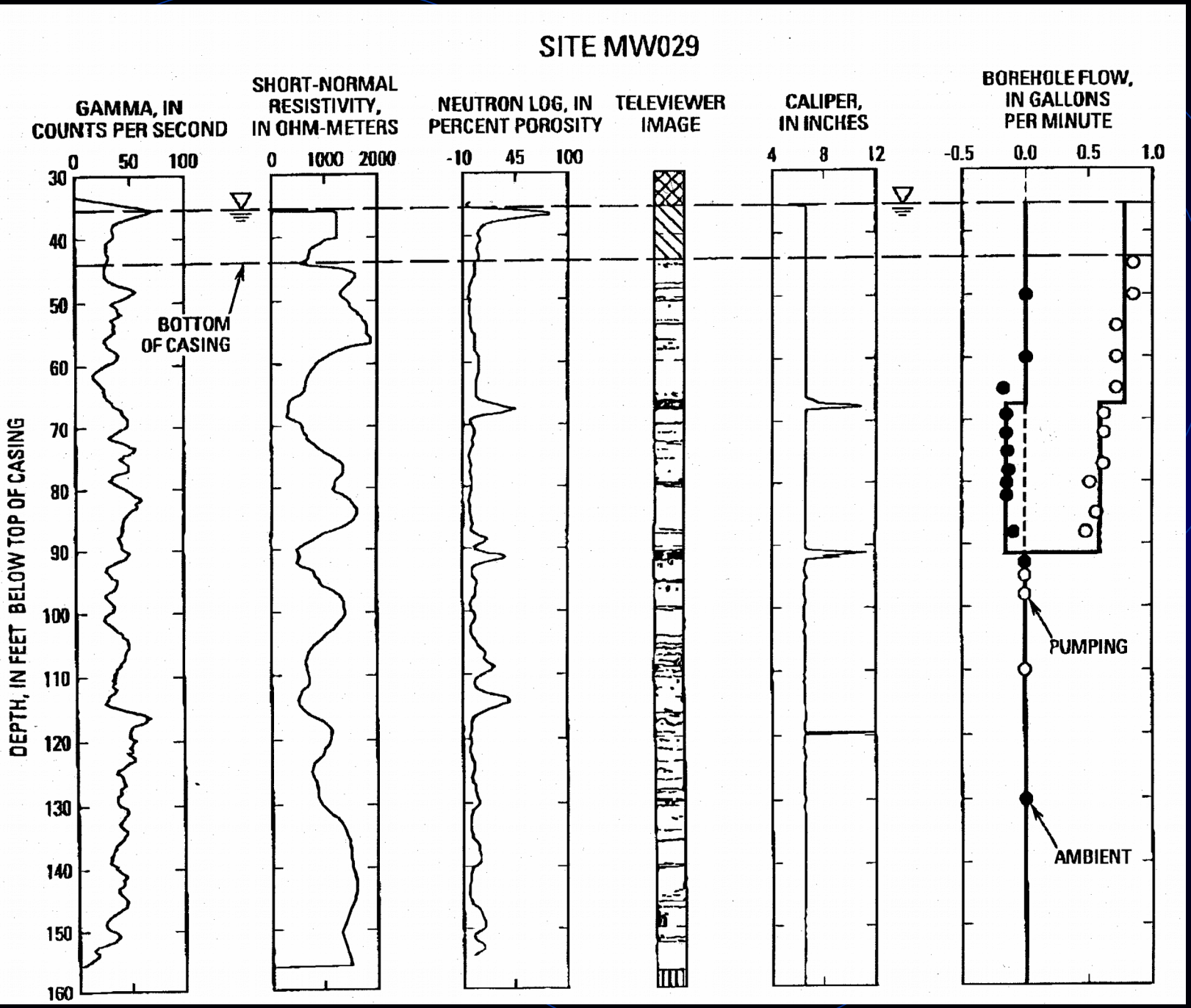


Background Geophysical Logging

- Suite of geophysical logs: gamma, formation resistivity, fluid column resistivity, induction, neutron, caliper, and acoustic televiewer.
- Identify potential water-producing zones, such as bedding planes, dissolution features, and fractures.
- Select zones to be used as measuring points for horizontal flowmeters and hydrophysics.

Logging to identify Vertical Flow

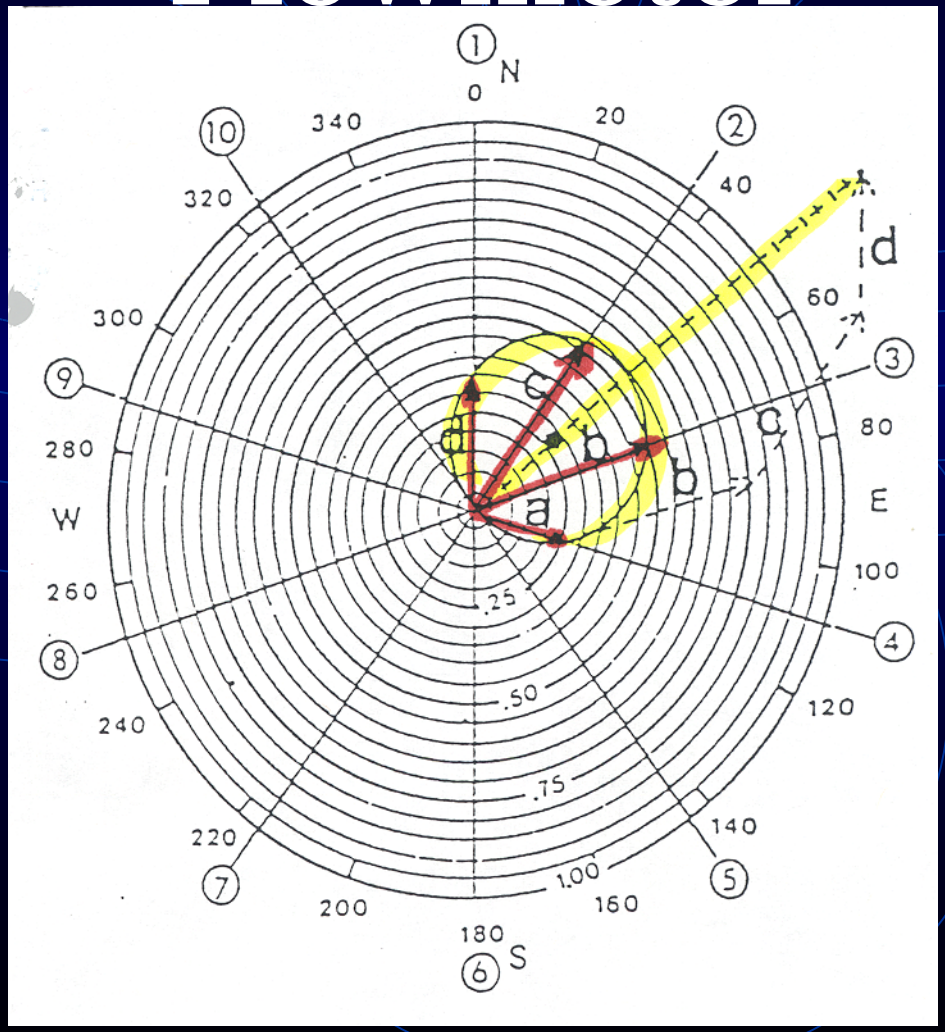
Vertical heat-pulse flowmeter


SITE MW029
GAMMA, IN COUNTS PER SECOND
0 50 100
SHORT-NORMAL RESISTIVITY, IN OHM-METERS
0 1000 2000
NEUTRON LOG, IN PERCENT POROSITY
-10 45 100
TELEVIEWER IMAGE
CALIPER, IN INCHES
4 8 12
BOREHOLE FLOW, IN GALLONS PER MINUTE
-0.5 0.0 0.5 1.0
DEPTH, IN FEET BELOW TOP OF CASING
30
40
50
60
70
80
90
100
110
120
130
140
150
160
BOTTOM OF CASING
PUMPING
AMBIENT

Evaluation Process

- Borehole camera used to identify depths for horizontal flowmeter measurements.
- Flowmeter measurements at specified depths in five test wells.
- Pumping of nearby well at Jefferson Proving Ground to induce horizontal flow.

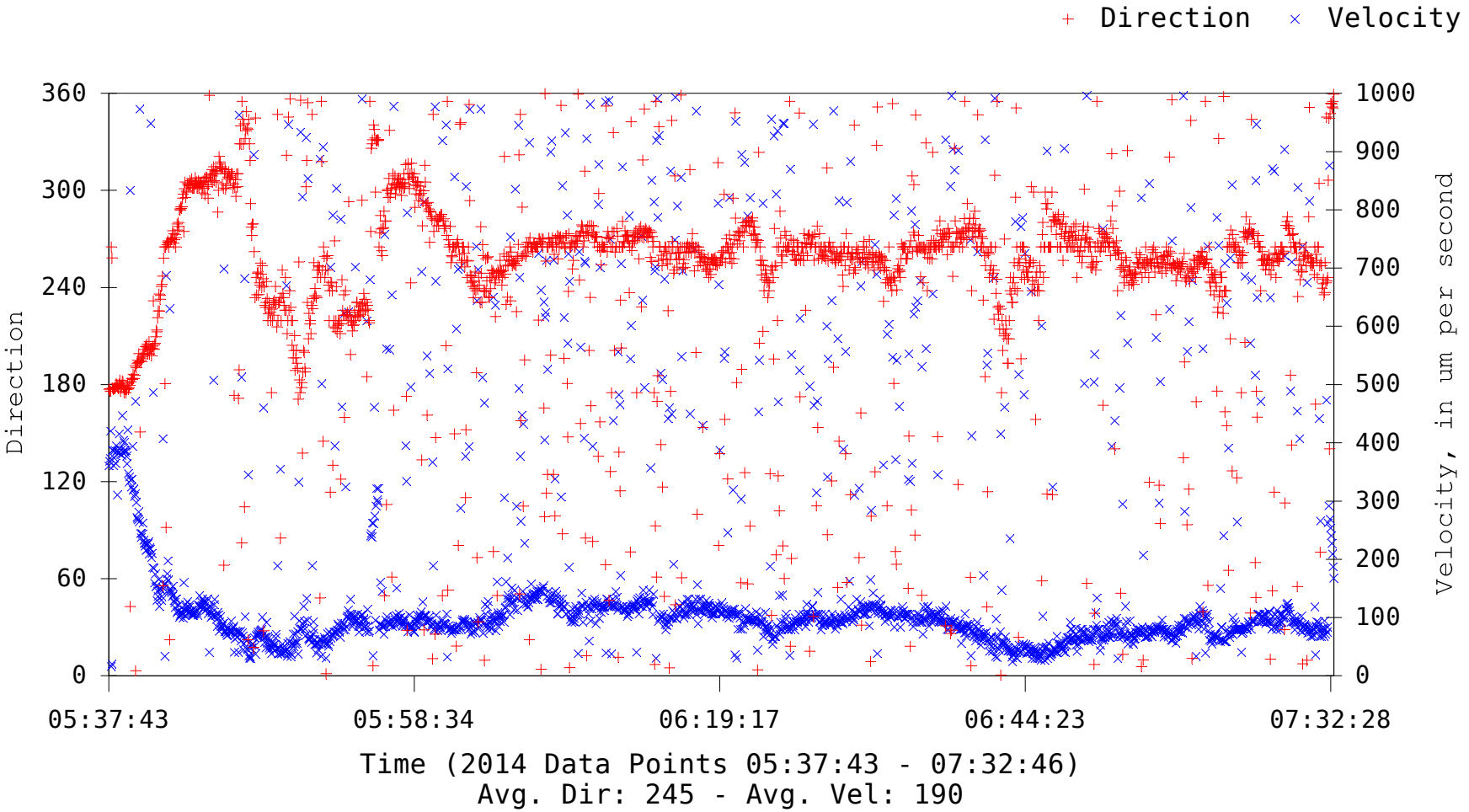
KVA Heat-Pulse Flowmeter



KVA Heat-Pulse Flowmeter

- Flow velocities 1-4 ft/day at different depths;
- Flow velocities and directions variable;
- Flow velocity increased and flow directions more variable during pumping of nearby well;
- Packer met resistance with borehole wall– no measurements in lower third of some wells;
- If packer was loose opposite cavities—

Colloidal Borescope



Colloidal Borescope

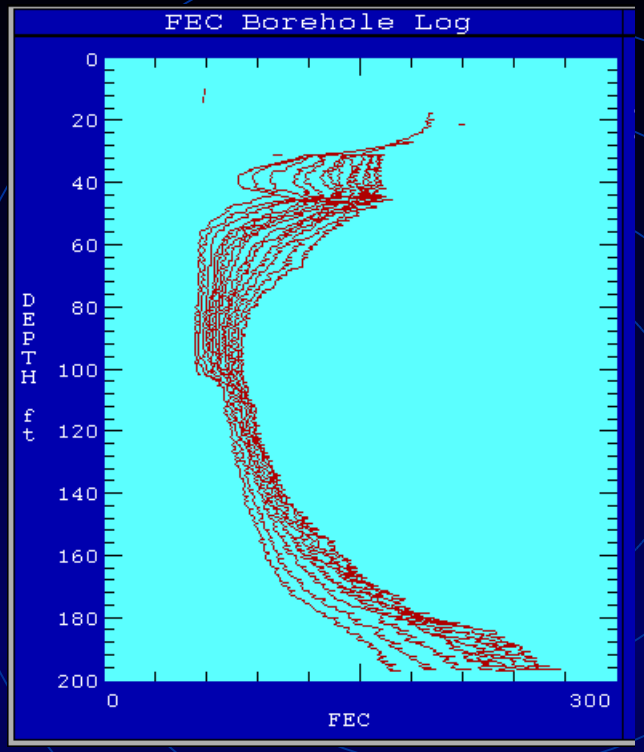
- Velocity and direction highly variable except at preferential flow zones;
- Consistent measurements opposite permeable rock or fractures, “swirling flow” above and below;
- Wider range and larger values for borehole velocity;
- During pumping of nearby well, average flow velocity

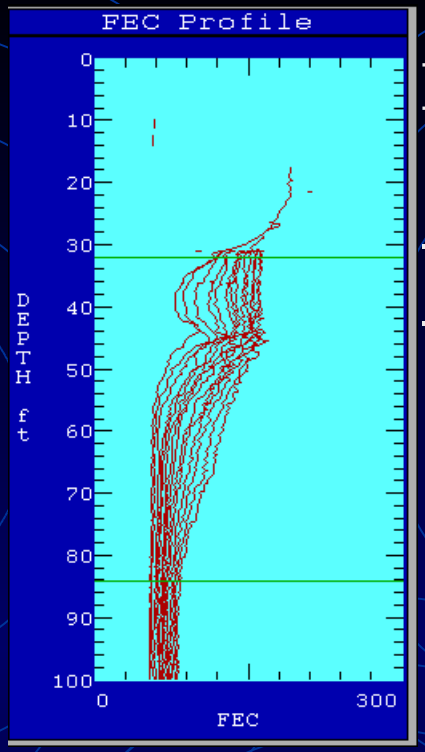
Acoustic Doppler Velocimeter

- Downward vertical flow in total length of wells
  (from falling sediment)—considered suspect;
- Adjustment for background noise, up to 3X;
- Flow directions & velocities variable through total
  length of both wells;
- Reasonably measured flow direction &

Hydrophysical Logging

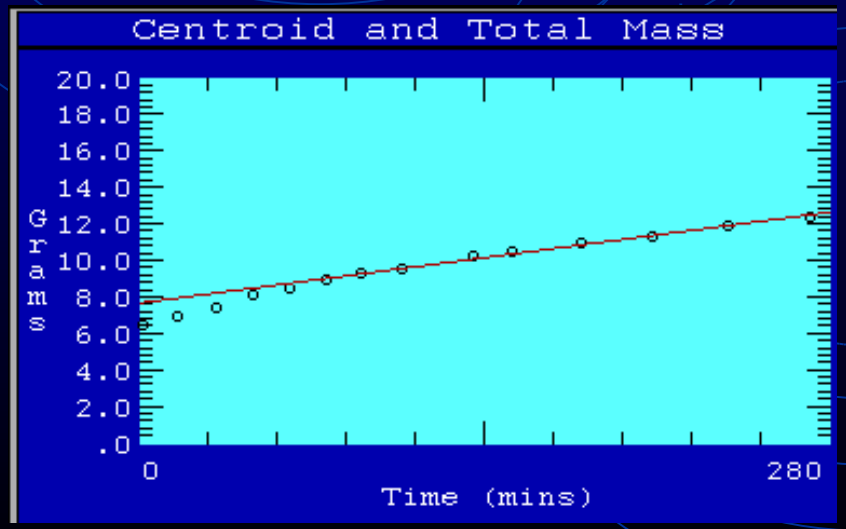
Provides estimates of flow velocity over a range of depths rather than discrete points;
Direction of flow not measured;
Horizontal and vertical flow can be measured;
Volumetric inflow rate (gpm) and velocity were calculated with mass flux analysis of repeated logs of fluid electrical conductivity (FEC);
Indicated connection of flow zones and increased velocity during pumping of nearby well

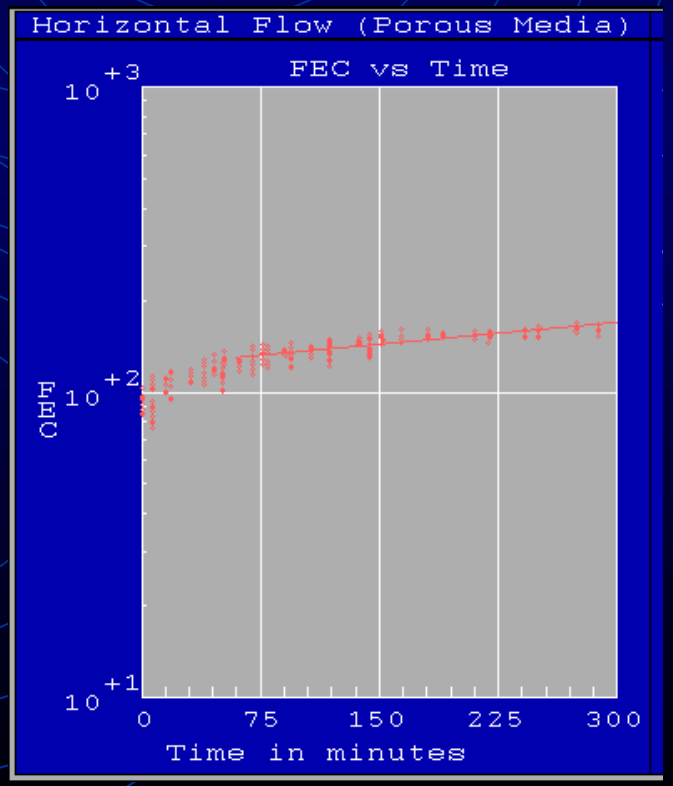




Hydrophysical Logging

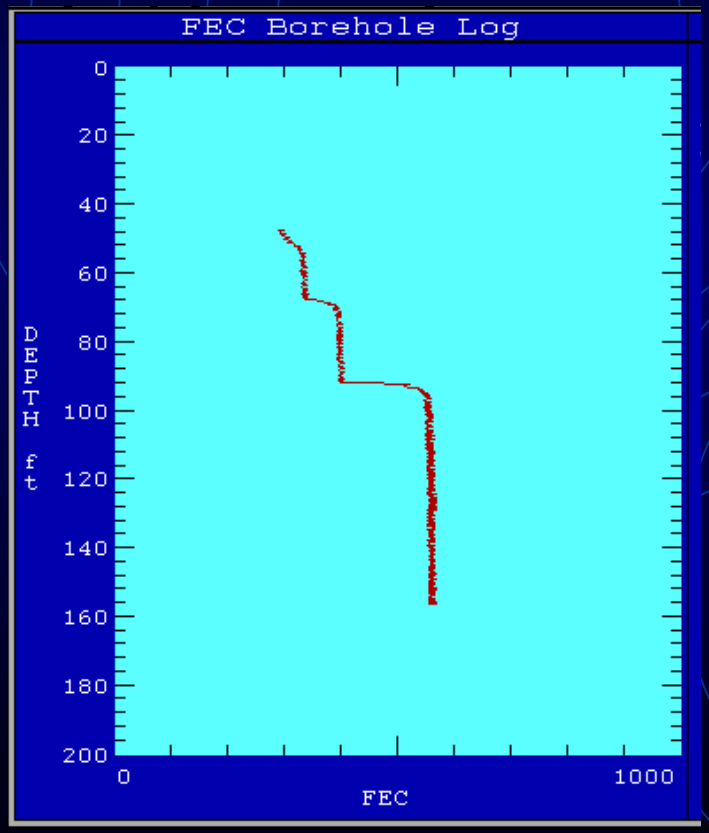
- Discharge 0.01 gpm
- Velocity 0.1 ft/day
  (at 42 to 46 ft)

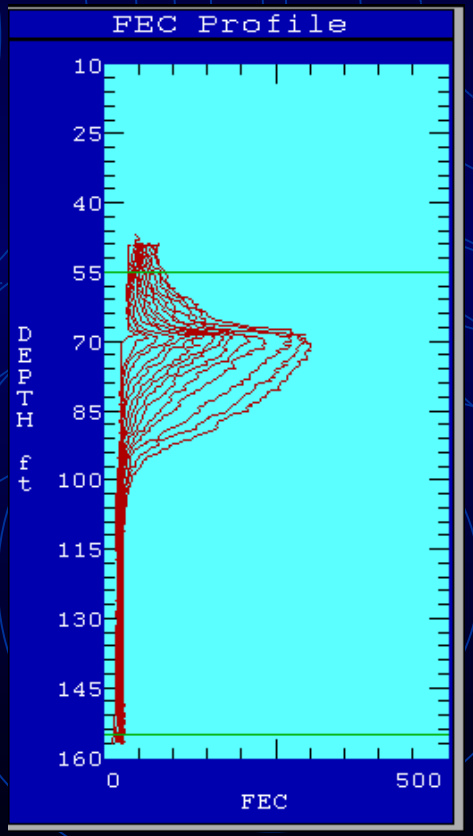


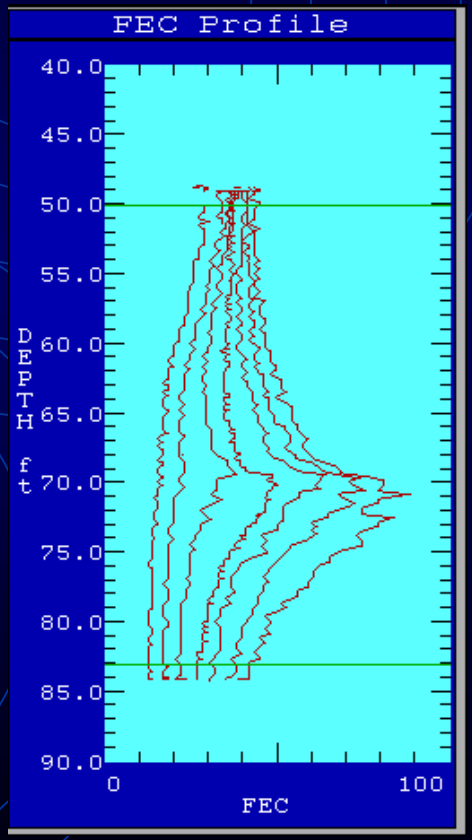


Hydrophysical Logging with Wireline Packer

(Paillet, Hess, and Williams, 1998)







Interim Observations

KVA Heat-Pulse Flowmeter

- Effective for identifying average horizontal flow directions, especially in absence of vertical flow;
- Horizontal flow velocities can be variable, particularly where packer was opposite cavities;
- Packer can prevent deeper measurements in some wells.

Interim Observations

Colloidal Borescope

- Continuous graphing identifies zones with flow;
- Zones with flow show more consistency in velocity and direction;
- Multiple exit fractures for vertical flow causes variability in horizontal flow measurements.

Interim Observations

Acoustic Doppler Velocimeter

- Experimental, two units in use in USGS;
- Lower resolution of 25 ft/day too high for most wells;
- Stabilization threshold velocity may need to be smaller;
- Standard method needed for “background noise”;
- Technology adjustment could have effect.

Interim Observations

Hydrophysical Logging

- Substantial requirement for logistics, equipment, personnel;
- Zones of largest horizontal flow can be identified;
- Inflow rates < 0.01 gpm may be below minimum
  this method;
- Volumetric inflow from hydrophysical logging was
  same as vertical downflow estimated

Interim Observations

General

- Borehole camera on rods provided exact depths of features for flow measurements.
- Methods may not agree because of low flow or vertical flow or both.
- Need to convert borehole velocity to aquifer velocity.
- Wireline packer could be useful for isolating flow for borescope and doppler.

USGS
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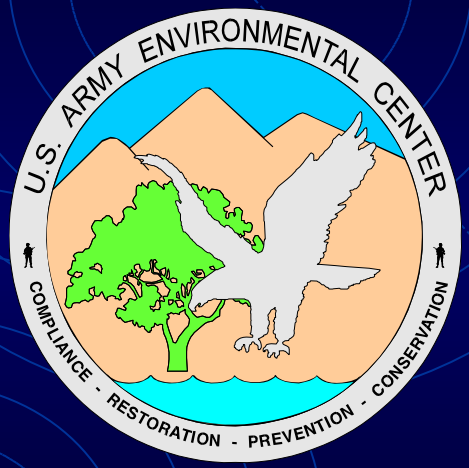
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